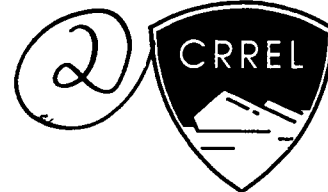


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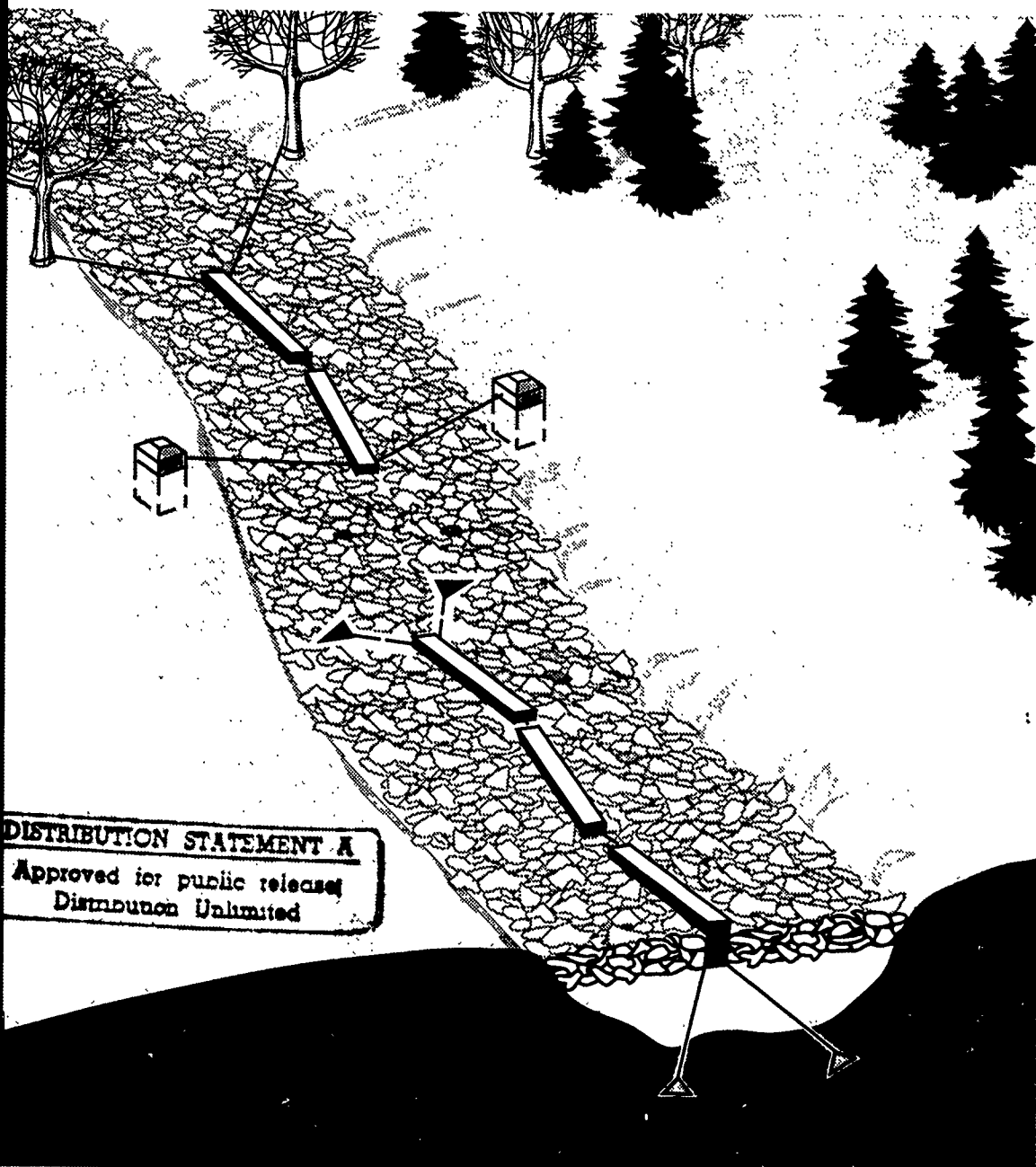
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Longitudinal Floating Ice Control Structures

A New Concept for Reducing Ice Jam Flood Levels

Darryl J. Calkins

September 1990



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**U.S. Army Corps
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Cold Regions Research &
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PREFACE

This report was prepared by Darryl J. Calkins, Supervisory Research Physical Scientist, Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this work was provided by the Office of the Chief of Engineers through the Water Resources of Cold Regions Research Program under Work Unit, CWIS 31722.

The author thanks Michael Ferrick of CRREL for his many technical discussions and his review of this report. A patent application has been filed on this new concept for ice cover control.

Longitudinal Floating Ice Control Structures

A New Concept for Reducing Ice Jam Flood Levels

DARRYL J. CALKINS

INTRODUCTION

The purpose of this report is to present a new concept for initiating thinner ice covers and reducing ice jam flood levels: an anchored, floating structure in the river, aligned in the streamwise direction. Its purpose is to take the load from a thickening ice cover or ice jam so that the accumulations are thinner and the corresponding river stages are lower.

A floating structure that can be installed prior to freeze-up in the fall and removed in the spring after ice-out would not significantly affect the riverine environment and should be relatively inexpensive compared to a full-depth permanent structure. Floating structures usually don't interfere with winter recreation or late-fall fish movement or migration.

LITERATURE REVIEW

Perham (1983), in a review of ice sheet retention structures, found no floating structures that had been sited longitudinally to reduce ice jam flood levels. All floating ice control structures were designed to go across the river. Booms have been designed to divert floating debris and are referred to as shear booms. Kennedy (1962) documented longitudinal log booms for restraining pulpwood in holding areas along rivers.

A full-depth, rock-filled gravity structure was placed down the center of the Ominawin bypass channel for the Lake Winnipeg regulation project.

Its purpose was to initiate a thinner ice cover earlier in the winter at reduced flows and also increase the ice cover stability when the flow discharge increased.* Belore (1986) discussed channel dividers as an ice control measure, but the structures he proposed were full depth, either sheet piling or rockfill material. Neither Belore nor Raban discussed a floating boom, nor did they analyze the potential effectiveness of the structures for reducing the water stages.

CONCEPT AND THEORETICAL DEVELOPMENT

The rationale for placing a continuous, partially submerged ice control structure, anchored appropriately along its length, in the streamwise direction is that the two submerged vertical surfaces of the structure will support the load transmitted by the ice cover. The concept is to decrease the effective river width by providing additional supporting surfaces in the river to take the ice cover load, which then results in a thinner ice cover accumulation (Fig. 1). The ice jam thickness at either freeze-up or break-up can be reduced, which will decrease the total river stage and for some situations will minimize flooding in low-lying areas.

Other structural arrangements could also have been analyzed using this approach. A structure

* Personal communication with Randy Raban, 1989.

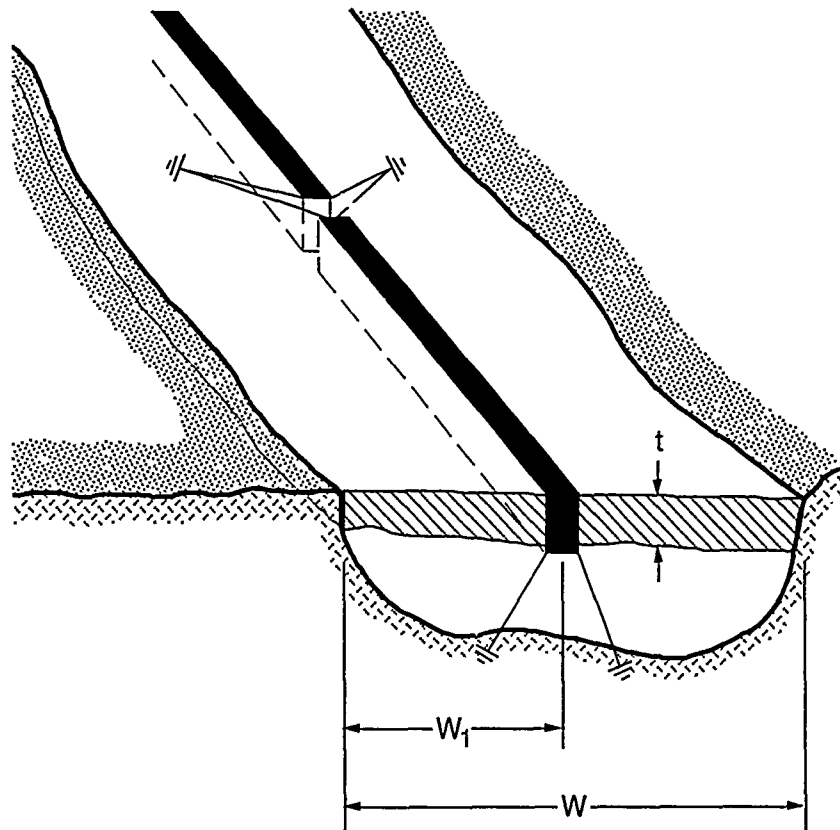


Figure 1. Conceptual view of a floating longitudinal ice control structure.

extending to the riverbottom or combinations of floating and full-depth structures are conceivable. To reduce the cost, gaps between structures may be possible without significantly increasing the ice jam thickness between structures.

The stresses developed within an ice jam are produced by the external fluid shear stress applied to the bottom of the jam and the weight component of the jam in the downstream direction over the width of the river. When the internal forces in the ice jam balance the external forces, the jam is in equilibrium and the stresses are transmitted to the shoreline or other resisting surfaces. If the effective river width is reduced by the placement of a structure along the channel, then the total shear stress and weight component forces of the jam will also be reduced. This means that the ice jam will be thinner when it reaches equilibrium.

These structures are initially conceived to be situated in rivers where the ice jam thickens during freeze-up and break-up by internal collapse or "shoving" of fragmented ice. (Applications to reduce ice discharge or retain ice at lake outlets

such as at Lake Erie or Lake Huron are envisioned as well.) Beltaos (1983) reviewed the theory for analyzing this thickening process. He improved the computational methodology for determining the thickness and verified the constants used in the theory for analyzing the mechanical properties of fragmented ice. The formulation of the equation for the thickness of a stationary ice jam is derived from a static force balance acting in an equilibrium section (Pariset et al. 1966). The equilibrium section is the point in the ice jam where the flow is steady and relatively uniform, the ice jam thickness carries the external loads to the shores, and the jam is not increasing in thickness. This force balance was substantiated by Beltaos (1983).

Applying the force balance equation to a river with an anchored, floating structure of finite length, placed down the channel with sufficient submerged depth to support the load from the ice jam on both sides (Fig. 2), yields

$$\text{bank resistance} = \text{fluid shear} + \text{cover weight}$$

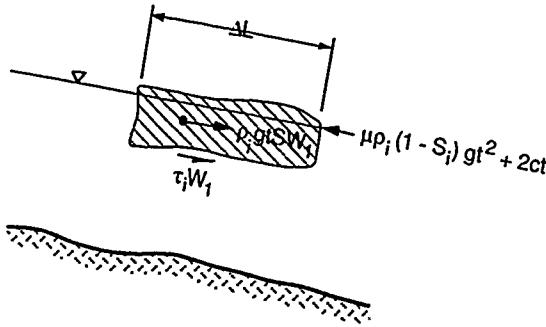


Figure 2. Components of driving and resisting forces on a length of ice cover.

or

$$\mu \rho_i (1 - S_i) g t^2 + 2ct = W_1 (\tau_i + \rho_i g S t) \quad (1)$$

where μ = frictional internal ice coefficient
 ρ_i = density of ice
 S_i = specific gravity of ice
 g = acceleration due to gravity
 t = thickness of the jam
 c = cohesion of the ice accumulation
 W_1 = width between boundaries (shore-boom or boom-boom)
 τ_i = fluid shear stress = $\rho g R_i S$
 S = bed slope
 R_i = hydraulic radius of the section influenced by the ice cover.

The hydraulic radius (Beltaos 1983) is

$$R_i = (2f_o)^{1/3} \left(\frac{f_i}{4f_o} \right) \left(\frac{q^2}{gS} \right)^{1/3} \quad (2)$$

where f_o = composite friction factor = $(f_i + f_b)/2$
 f_i = friction factor for the ice cover underside
 f_b = friction factor for the riverbed
 q = unit discharge (the total river flow divided by the river width assuming a relatively wide rectangular channel).

When the fluid shear τ_i is substituted into eq 1, the thickness of an equilibrium ice jam, after some algebraic manipulation following the Beltaos (1983) approach but including the cohesion term, can be determined from

$$t = \frac{W_1 S}{2\mu(1-S_i)} \left\{ 1 + \left[1 + \frac{(2f_o)^{1/3} \mu (1-S_i) (f_i) (q^2/gS)^{1/3}}{S_i} \right. \right. \\ \left. \left. - \frac{4c}{\rho_i g W_1 S} \left(1 - \frac{c}{\rho_i g W_1 S} \right) \right]^{1/2} \right\} - \frac{c}{\rho_i g \mu (1-S_i)} \quad (3)$$

It is apparent in eq 3 that the thickness of the accumulation depends primarily on the river slope, the width between the supporting boundaries, and the cohesion of the fragmented ice cover. If the cohesion term is assumed to be constant, then a decrease in the thickness of the accumulation can be expected by decreasing the stream width or slope. Changing the river slope is usually difficult without significant environmental impact (for example, building a dam), but adding additional resisting surfaces such as a floating boom in the river to decrease the effective width seems to be a reasonable approach.

The cohesion term is important because it reduces the thickness of an equilibrium ice cover at freeze-up. Pariset et al. (1966) report calculated values of ct of 1100–1300 N/m. Calkins (1984) used a cohesion value of 1000 N/m² for the Ottawa-Quebec River at freeze-up to calculate the measured ice cover thicknesses.

The major stresses transmitted through the jam to the streamwise floating ice control structure and to the banks are the normal and shearing stresses developed within the ice jam. If the ice covers on both sides of the floating structure are of equal thickness, the normal forces F_n on the structure cancel each other (Fig. 3). The remaining force F_t is derived from the streamwise shear of the ice jam acting in the downstream direction against both vertical faces of the structure. As Uzuner and Kennedy (1976) have demonstrated, the determination of this shear force is based on scant laboratory data with a wide range in the coefficients because the strain rate of ice fragment deformation is a dependent variable, varying with fragment size, distribution, applied load, etc. The distribution of this shear stress within the ice jam thickness is not known.

Uzuner and Kennedy's (1976) relationship for the streamwise shear strength τ_s of the ice jam in a static situation is

$$\tau_s = C_o \sigma + C_i \quad (4)$$

where C_o = shear stress constant (ranging from 2 to 100)

C_i = cohesive intercept ($\sim 50 \text{ N/m}^2$)

σ = normal stresses in the cover = $\rho_i(1-S_i)(1-p)gt$

p = cover porosity.

The resisting upstream force R for a floating ice control structure placed down the center of the channel when the normal forces cancel each other is $R = 2\tau_s tL$, where L is the length of the structure, but the range in the resisting force is large because of the uncertainty of the coefficient C_o in eq 4. More experimental laboratory and field data are needed to quantify these coefficients; otherwise the structure will have to be oversized, making it more expensive than necessary.

There are apparently no dynamic ice load ex-

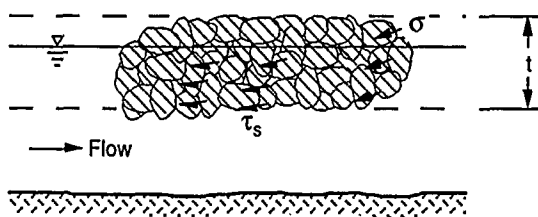
periments with a structure like the one proposed here, but Ferrick and Mulherin's (in press) numerical model can predict longitudinal dynamic loads during ice cover movement.

CASE STUDY

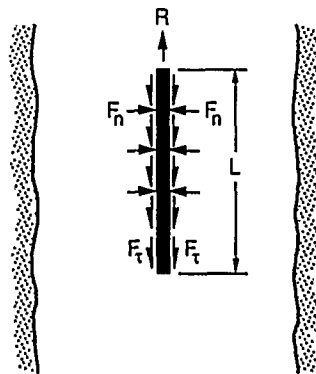
To illustrate a potential application of this technique, the analysis is applied to the ice jam flooding problem on the Salmon River in Salmon, Idaho. It is assumed that the cover thickens by internal collapse through the damage reach because "narrow" river ice jams cannot form in this reach. Narrow river ice jams form when the advancing cover is strong enough so that it does not shove to greater thicknesses to sustain the driving forces of fluid shear and the weight component. The limiting criteria given by Beltaos (1983) for a narrow jam to exist with a thickness-to-stage ratio of 0.33 is that the river width-to-stage ratio W/H must be less than 8.5; Salmon River data show that W/H is 20-30, so narrow river ice jams are not possible here.

Floating longitudinal structures placed equal distances apart in the streamwise direction will be analyzed. A structural design of the concept will not be undertaken, but it is likely that a satisfactory anchoring system can be deployed, as Perham (1983) gives many suggestions. The depth of the structure is equal to the thickness of the ice jam, plus some margin of safety. A floating structure was chosen instead of one extending to the riverbed because a floating structure could allow for possible flow and ice redistribution over the cross section as the ice jam forms. A fixed, full-depth structure might not maintain a uniform flow split and a uniform incoming ice discharge at the upstream end, which could result in different flow intensities q and hence different ice jam thicknesses in the channels. This may be desirable in navigational channels, where thicker or thinner covers may be important for certain conditions.

The river width is roughly 60 m with a slope of 0.003 through the town of Salmon (U.S. Army Corps of Engineers 1984, 1986). The ratio of ice friction factor to the composite friction factor is taken as 1.25 based on data from several ice jams (Beltaos 1983), and the ice properties $\mu = 1.2$ and $S_i = 0.92$ are held constant. Field data at the site were not available to make estimates of the friction factors or check ice jam thickness calculations, but total river stage data from USGS records were available.



a. Side view.



b. Plan view.



c. Cross section.

Figure 3. Forces applied to a floating longitudinal structure.

Table 1. Computations of ice jam thicknesses, flow depths and stages with zero cohesion.

No. of structures	Spacing W_1 (m)	Ice jam thickness (m)	Flow depth (m)	Total stage (m)
Case 1: $Q = 22.65 \text{ m}^3/\text{s}; f_o = f_i = f_b = 0.2$				
0	60	2.22	0.62	2.66
1	30	1.25	0.62	1.77
2	20	0.91	0.62	1.46
Case 2: $Q = 22.65 \text{ m}^3/\text{s}; f_o = 0.3; f_i = 0.375$				
0	60	2.27	0.71	0.80
1	30	1.29	0.71	1.90
2	20	0.94	0.71	1.57
3	15	0.76	0.71	1.41
Case 3: $Q = 22.65 \text{ m}^3/\text{s}; f_o = 0.5; f_i = 0.625$				
0	60	2.3	0.85	2.99
1	30	1.3	0.85	2.08
2	20	0.9	0.85	1.76
Case 4: $Q = 34 \text{ m}^3/\text{s}; f_o = 0.3; f_i = 0.375$				
0	60	2.29	0.94	3.05
1	30	1.30	0.94	2.14
2	20	0.9	0.94	1.82
Case 5: $Q = 34 \text{ m}^3/\text{s}; f_o = 0.5; f_i = 0.625$				
0	60	2.44	1.11	3.34
1	30	1.42	1.11	2.42
2	20	1.06	1.11	2.08

The ice jam thickness between the bank and the floating structures (equally placed across the river) are analyzed using eq 3 with the cohesion term taken as zero for the initial calculations. Equal spacing between the structures was chosen because unequal widths would result in ice jam thicknesses of different values, and this would violate the uniform, one-dimensional flow assumption of a constant unit discharge across the channel. Table 1 shows the results from the computation of the ice jam thicknesses for two flow conditions and three composite friction factors, as well as for varying numbers of structures. The total river stage is composed of the flow depth beneath the cover plus the submerged portion of the ice jam.

The baseline ice jam thickness of 2.2–2.4 m (no structure) computed for the five cases with a river width of 60 m appears reasonable for the site, as Cunningham and Calkins (1984) measured thicknesses in excess of 3 m downstream of Salmon in reaches of similar hydraulic geometry and river slope, but a portion of this is probably from frazil ice deposition. The computed river stages also appear reasonable, because a review of the USGS stage data at the site reveals that ice-jam-related stages range up to 3 m, which is similar to the computed stages without a structure. The computed flow velocities are low compared to measurements taken in 1983, but detailed cross-sectional properties weren't used and the available

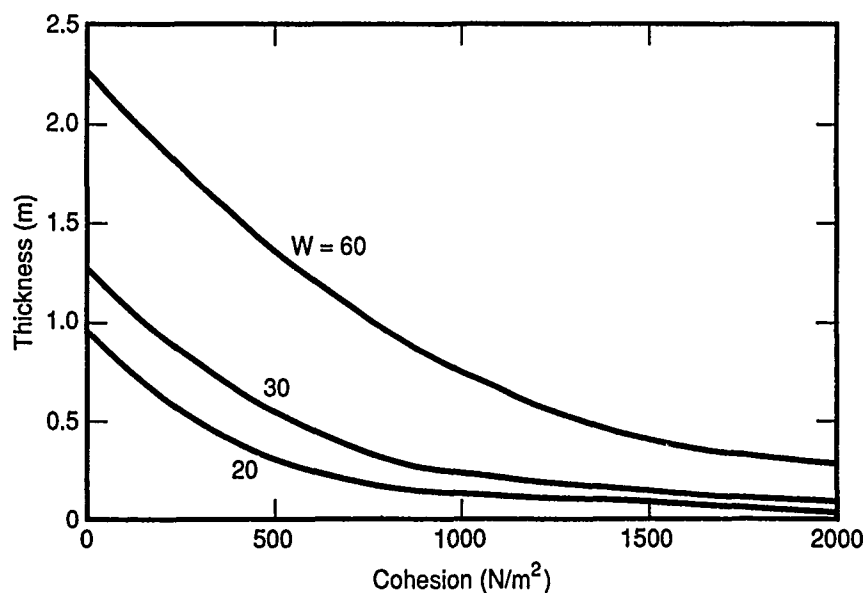


Figure 4. Ice cover or ice jam thickness vs cohesion for a river with no structure or with one or two structures (using hydraulic data from case 2).

data are not sufficient to calculate ice or bed friction factors independently.

When a structure is placed down the center of the channel, the ice jam thickness decreases by nearly 1 m for all cases; this translates to about a 0.9-m drop in water level. When two structures are used, the stage is reduced by 1.2 m. These changes in ice jam thickness are consistent for each case studied.

The assumption was made that the friction factors would be constant and independent of ice jam thickness because field data at the site were not available to do a detailed analysis. However, it has been shown that ice jam roughness decreases with thickness (Beltaos 1983), and the total river stage computations may be conservative because the flow depths may be overestimated for the thinner ice conditions.

To illustrate the impact of the cohesion term c on the computed ice cover thicknesses, the hydraulic data for case 2 are used. Figure 4 shows the ice thickness computed using eq 3 for different cohesion values for the river with no structures and with one and two structures. If a cohesion value of 500 N/m² is used, the ice thickness with one structure in the center of the channel is 0.8 m lower than it would be without the structure; if a cohesion value of 0 is used, the difference would be 0.97 m. A greater value for the cohesion, say 1000 N/m², would show only a 0.5-m change in thickness.

DISCUSSION

An ice control structure placed in the streamwise direction significantly reduced the computed ice jam thickness for this site in Salmon, Idaho, and additional analysis is warranted. Actual field data on ice jam thicknesses, water surface slopes, river stage and river cross sections would permit a refinement of these initial computations.

The results in Table 1 show that a 150% increase in the composite friction factor (from 0.2 to 0.5) for the same discharge produces only a 0.17-m effect on the ice jam thickness and a 0.23-m increase in the flow depth for a total stage change of 0.40 m. This result indicates that the gravitational force due to the ice jam weight component in the streamwise direction is the major driving force because of the large thickness. The ice jam roughness friction factor contributes about 10–15% to the total load on the accumulation at this site because the river slope is steep.

Since the change in ice jam thickness was expected to be much larger, the contributions to the ice jam thickness from both the fluid shear stress and the downstream weight component were computed using eq 1 with a cohesion value of 0 and the results from case 2 shown in Table 1. Table 2 gives the percentage of the ice jam thickness that each term contributes to the total thickness. With no in-stream structure, the shear stress contribution is roughly 15%, but as the cover becomes thinner with structures placed in the channel, the shear stress contribution increases to almost 35% with three structures placed down the channel.

Results by Calkins (1983) for streams with similar bed slopes indicates that the ice jam weight component generally contributed 60–70% of the total thickness. It appears the ice jam thicknesses computed for the Salmon River without any structure may be slightly high and the flow depths low. Field data would help verify this point.

If the cohesion term were included in eq 3, then reduced values of ice jam thickness can be expected, which may be appropriate for freeze-up jams during extremely cold periods. However, determining the proper value for the cohesive contribution is not yet clear.

Realistic values for cohesion at the Salmon River site appear to be between 200 and 500 N/m² in order to predict reasonable ice cover thicknesses with no structure. If the cohesion intercept of 50 N/m² is used for c , based on work reported in Uzuner and Kennedy (1976), and case 2 with no structure is selected, the ice jam thickness reduces to 2.10 m, not a significant change from 2.27 m.

The reason for the difference between the laboratory data and the cohesion values used to get reasonable ice thickness reductions appears to lie in how the cohesion term is interpreted. The laboratory tests discussed by Uzuner and Kennedy

Table 2. Contributions of the shear stress and the weight component to ice jam thickness for case 2.

No. of Structures	Contribution to ice jam thickness (%)		
	Width	Shear stress	Weight component
0	60	14.7	85.3
1	30	23.8	76.2
2	20	29.8	71.2
3	15	34.9	65.1

(1976) were conducted with fragmented ice at just above the freezing point, yet some researchers feel that the use of the cohesion term compensates for the freezing of the upper layer of the accumulating ice cover, which wasn't a parameter in Merino's (1974) work. It is questionable if a soil mechanics approach is adequate for determining the resistive strength of this upper frozen layer, but the present approach appears to work.

The shape and type of structure that could be placed in the river and that could resist the static and dynamic loads have not been analyzed. It is doubtful that a traditional ice boom shape is optimal, and the connection details are likely to be different. Even the materials used for a structure placed longitudinally may be different from the conventional wood or steel. It is possible that geosynthetic materials, matted tires or open lattice compartments may be appropriate load-bearing surfaces. Floating breakwater designs should be evaluated (McCartney 1985).

The change in the break-up regime has not been quantified yet. According to Ferrick and Mulherin (in press), the additional ice attachment surfaces offered by a longitudinal floating structure would probably increase the break-up resistance relative to the natural condition as long as the bond between the ice and the structure remains. However,

the support to the ice provided by the structure in the center of the channel may be different than that at the riverbanks. More analysis, observations and thought are needed.

ICE COVER INITIATION

Initiating an ice cover using floating longitudinal structures and a conventional cross-river ice boom is another concept to consider. Closely spaced longitudinal structures placed near where an ice bridge is desired would take the load of a thin accumulation. The conventional boom would hold the ice when the ice discharge is low between the longitudinal booms. With a pattern of fewer and fewer structures upstream from the boom (Fig. 5), the thickness of the accumulation would increase in the upstream direction. This gradual increase in thickness upstream is important because the river stage would attain its "natural progression stage" gradually instead of abruptly.

Floating streamwise structures also have the potential for aiding in the progression of an ice cover through rapids. For example, if the ice cover thickness and length were insufficient in a pool just downstream of the rapids to cause the cover to advance over it, longitudinal structures placed

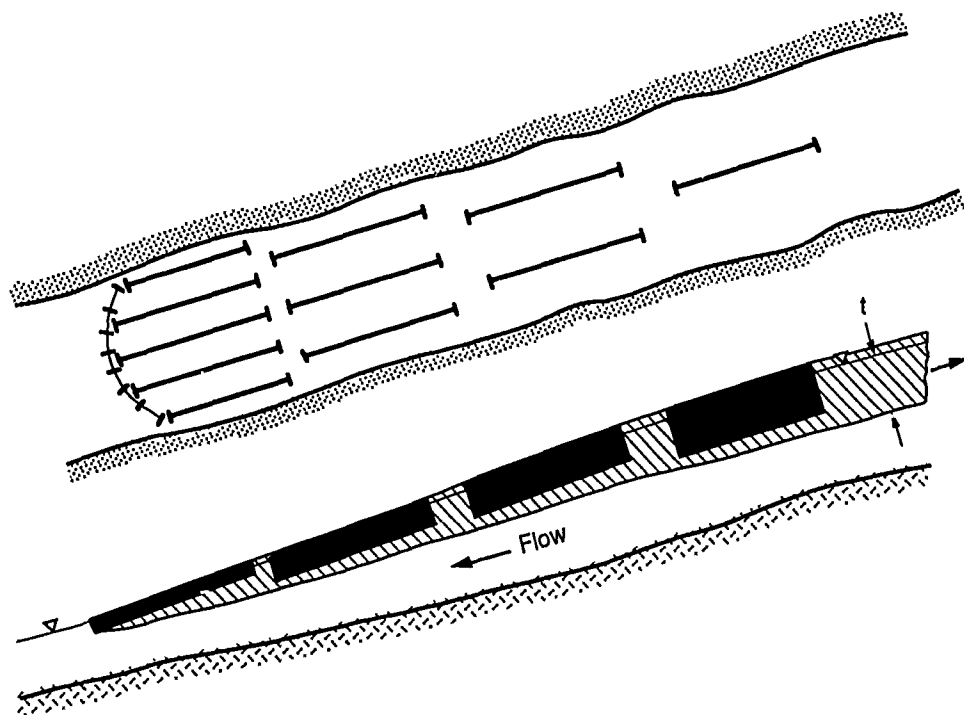


Figure 5. Conceptual plan for developing an ice cover in a river reach with high flow velocities.

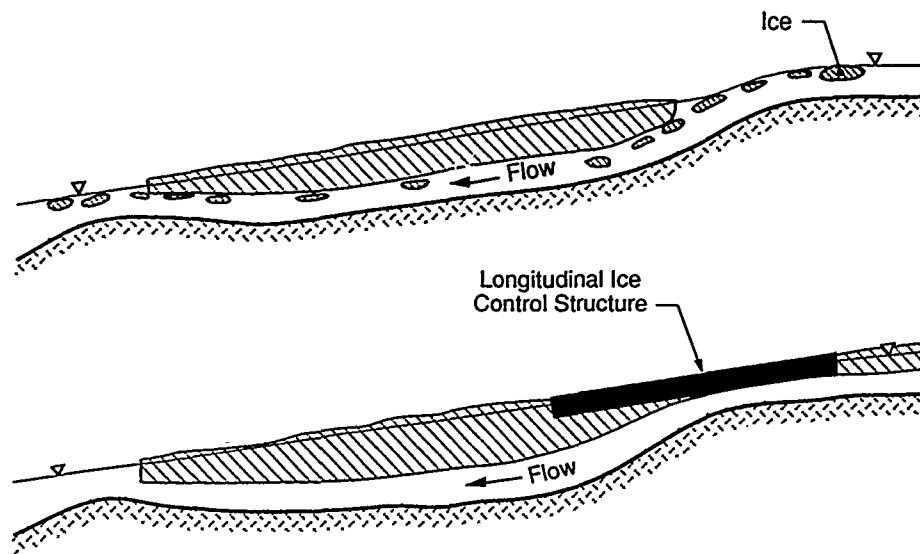


Figure 6. Use of a floating structure to assist in staging an ice cover through a high-velocity region (i.e. rapids).

into the pool and up through the rapids might help the cover progress through it at a lesser thickness (Fig. 6). Conversely, if the ice cover was too thick in the downstream pool and created flooding before the ice cover could progress over the rapids, a longitudinal boom could allow a thinner cover to develop through the entire reach.

CONCLUSIONS

Streamwise floating structures have the potential for reducing the thickness of ice jams in rivers by reducing the effective width of the channel, one of the major factors determining ice jam thickness. Floating structures would be relatively inexpensive and environmentally benign; they would also be able to move in the channel so that the ice forces on their long sides would be equal. Depending on the local conditions and problems, these structures could be arranged in various configurations, or they could be used in combination with full-depth permanent streamwise structures or traditional cross-river ice booms. Floating structures would be useful both at freeze-up and at break-up, although they may not be able to withstand the dynamic forces of a break-up ice jam.

The theory for ice jam accumulations was modified to analyze floating streamwise structures. Calculations for a section of the Salmon River in Salmon, Idaho, show that the river stage during an ice jam could be reduced by as much as

0.9 m if a single streamwise structure is used. If more than one structure is used, the stage would be decreased further. The length, shape and anchoring system of the structure were not addressed. Because detailed data were not available for the Salmon River, reasonable approximations had to be made for the cohesion force; however, in steep rivers like the Salmon, the gravity component of the ice is much more important than cohesion in determining ice thickness, so the analysis is still valid.

Laboratory model studies and field tests should be undertaken to verify some of the non-uniform conditions that can't be simulated with a one-dimensional analysis, as well as to evaluate the coefficients in the relationship for streamwise ice cover shear stress, particularly the cohesive contribution. Additional calculations are needed using more-detailed river and ice data for the Salmon River site. Ferrick's break-up model might be a tool to use in assessing how a structure would change the break-up regime.

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